

Massive Stars in the SMC

D.J. Lennon

Isaac Newton Group of Telescopes, Apartado 321, E-38700 Santa Cruz de La Palma, Spain; Instituto de Astrofisica de Canarias, E-38205 La Laguna, Tenerife, Spain

C.J. Evans

Isaac Newton Group of Telescopes, Apartado 321, E-38700 Santa Cruz de La Palma, Spain

C. Trundle

Instituto de Astrofisica de Canarias, E-38205 La Laguna, Tenerife, Spain

Abstract. In this paper we discuss how the Small Magellanic Cloud is the ideal laboratory in which to study massive stars in a low metallicity environment. We review the observational data for OB stars in the SMC concentrating on those aspects of their spectra which provide information on processes which may strongly influence their evolution, namely mass-loss, rotational mixing and mass-transfer. We illustrate the very weak winds now thought to pertain to late O-dwarfs in the SMC, using HST/STIS observations of the main sequence in the very young cluster NGC 346, briefly discussing the quantitative results for these stars, and the difficulties involved in their determination. We show how stars with similar luminosities can have different luminosity classes while stars with similar spectral types and luminosity classes can have significantly different luminosities. These discrepancies can be interpreted as evidence for rotational mixing on the main sequence. While the weak winds of the dwarfs present serious difficulties for the determination of wind terminal velocities we show that the supergiants have terminal velocities comparable to OB supergiants in the Milky Way, in reasonable agreement with theory. We also summarize recent work demonstrating that the temperature dependence of wind terminal velocities does not follow the widely adopted step-like approximation, the bistability jump around spectral type B1 does not occur for normal stars. Finally we review surface compositions of OB stars in the SMC finding that 42 out of 45 OB stars with detailed surface abundances are enriched in nitrogen by a factor ~ 10 or more. While these enhancements are consistent with those produced by models with rotational mixing the rotational velocities of the sample are significantly lower than the values predicted by the models, indicating a possible problem with the evolution of angular momentum in the models or possibly in the efficiency of mixing. In this context we comment on the biases present in the stellar samples discussed in the literature.

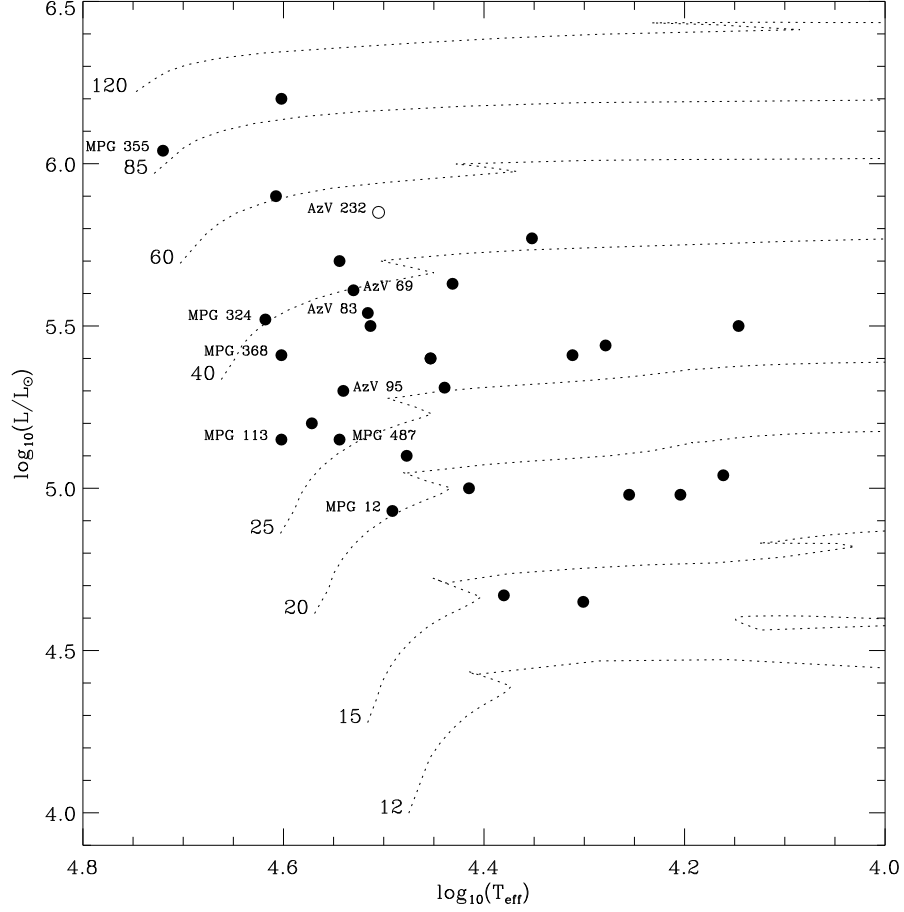


Figure 1. HR diagram illustrating the position of the SMC stars observed in HST/STIS GO programmes 7437 and 9116 (filled circles). The evolutionary tracks are from Charbonnel et al (1993) for approximate SMC metallicity and without rotation. Luminosities and effective temperatures are taken from the sources discussed in Evans et al (2004b). The stars labelled with MPG numbers (Massey et al 1989) are all in the SMC cluster NGC 346, their spectra are illustrated in Fig.2. Those labelled with their AzV numbers are the O7 supergiants and giants discussed in section 3 along with the additional O7 Iaf+ star AzV 232 (open symbol).

1. Introduction

The Small Magellanic Cloud (SMC) has a special significance in the study of massive stars due to the fact that its metallicity (Z) is approximately $1/5^{\text{th}}$ solar. This importance stems from the fact that mass-loss rates scale very roughly as \sqrt{Z} which implies that we should see significant differences in mass-loss rates of SMC OB stars with respect to similar stars in the solar neighbourhood. The crucial corollary to this is the fact that mass-loss is a major factor influencing massive star evolution, and if we also consider suggestions that stellar rotation

may well depend on Z , it is clear that the SMC is the ideal laboratory in which to study massive stars and their evolution at low Z .

There are additional practical reasons which make the SMC the ideal environment in which to carry out these studies: The well determined distance of the SMC enable us to deduce accurate stellar radii, which are important in the application of unified model atmosphere/wind models, and allow us to deduce spectroscopic masses for comparison with predictions of stellar evolution calculations. The low extinction towards the SMC gives us access to the wind diagnostics in the near- and far-ultraviolet regions of the spectrum, and particularly allows us to determine wind terminal velocities from saturated P-Cygni lines. It is perhaps not generally appreciated that due to extinction it is impractical to observe all but a handful of OB stars in our galaxy in the FUV. Finally, the nitrogen abundance of the SMC is much lower than the mean metal deficiency in the SMC, being only about $1/30^{\text{th}}$ solar. This permits an easy detection of surface nitrogen anomalies from different processes such as mass-loss, mixing and mass transfer. The objective of this review is therefore to look at recent observational programmes which concentrated on the SMC and highlight some results concerning mass-loss, stellar rotation and surface compositions of massive stars in that galaxy.

Perhaps the definitive ultra-violet spectroscopic survey of massive stars in the SMC to date is represented by the survey discussed by Walborn et al (2000) and Evans et al (2004b), the sample's coverage of the HR diagram being illustrated in Fig.1. These data were obtained in two separate Hubble Space Telescope (HST) programmes, GO7437 concerning O-type stars, and GO9116 concerning B-type stars, the medium resolution echelle mode of the Space Telescope Imaging Spectrograph (STIS) was used for both programmes. A general consideration for the target selection was to distribute targets throughout the upper HR diagram but ensuring that we obtained spectra of stars close to the previously unexplored low luminosity O-type dwarfs. This latter constraint was achieved by targetting O-type stars in the very young SMC cluster NGC346, while low luminosity giants were observed in the rather older cluster NGC330, other giants and supergiants being chosen from the catalogues of Azzopardi & Vigneau (1975, 1982), though using the spectral types of Garmany et al (1987), Massey et al (1989), Lennon et al (1993) and Lennon (1997). In choosing the targets it was noticed that there was an O7Iaf+ star (AzV 83) with a visual magnitude in the range occupied by O7III stars and this was added to the target list together with an O7III star (AzV 69) of similar magnitude. In our subsequent discussion of the observed properties of SMC massive stars we concentrate on results derived from this sample, although we include some results from other notable observational programmes. We only briefly discuss mass-loss, since a more thorough discussion of this topic is provided elsewhere in these proceedings via the contributions of Alex de Koter and Trundle et al.

2. O-stars with weak winds

The exceptional weakness of stellar wind features in the SMC O-type dwarfs was first illustrated and discussed by Walborn et al (1995), this being enhanced by the Walborn et al (2000) study, referred to above, which extended coverage

of the HR diagram to lower masses and luminosities than had previously been achieved. The O-type dwarf sequence, as represented by the stars in NGC346, is a particularly good illustration of the weak wind features in SMC stars (Fig.2), the late O-type stars exhibiting almost no sign of the characteristic P-Cygni wind features usually associated with O-type stars. Optical spectra of these objects confirm the weakness of their winds in the the lack of significant in-filling or emission of the $H\alpha$ line, usually a primary diagnostic of the mass-loss rate.

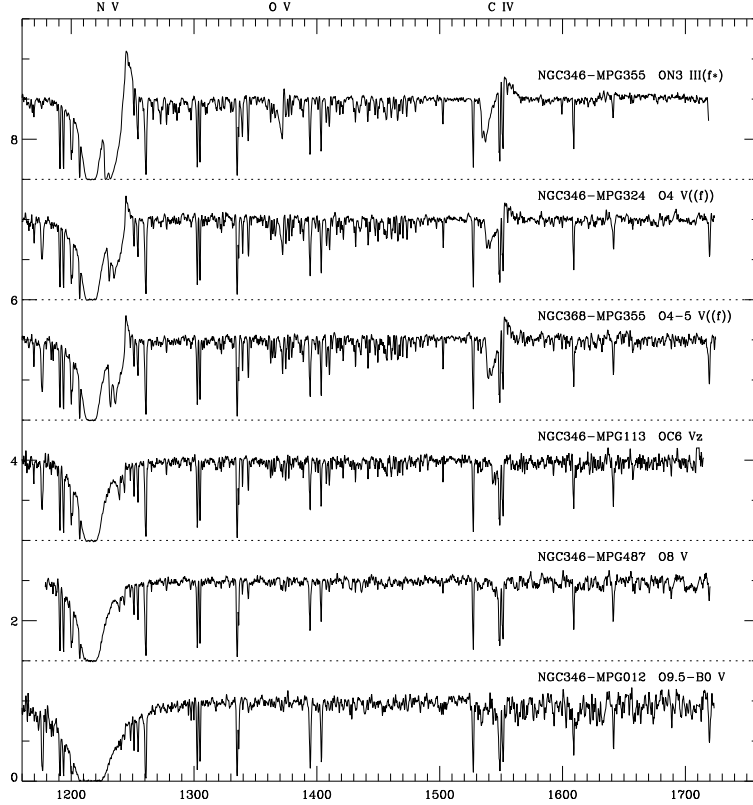


Figure 2. Illustration of the HST/STIS UV spectra for the O-type dwarf sequence in the SMC cluster NGC346. Notice how the P-Cygni wind features of the N V and C IV lines fade away towards the later spectral types.

This theme was followed up by Bouret et al (2003) who determined mass-loss rates for the NGC346 stars using CMFGEN to model the *weak* wind features in their UV spectra. The surprising result was that the lower luminosity dwarfs MPG113 (O6 Vz), MPG487 (O8 V) and MPG12 (O9.5-B0 V (N str)) have mass-loss rates which are one to two orders of magnitude lower than those predicted by the theory of Vink et al (2001), Fig.3. Independent corroboration for this result was provided by Martins et al (2004) who analysed the spectra of a further 4 SMC dwarfs and found similar results (also illustrated in Fig.3). It is not clear why low metallicity O-type dwarfs appear to have such weak winds, obviously clumping only exacerbates the problem. A major problem in the interpretation is that the winds are so weak that the $H\alpha$ line in these stars, normally

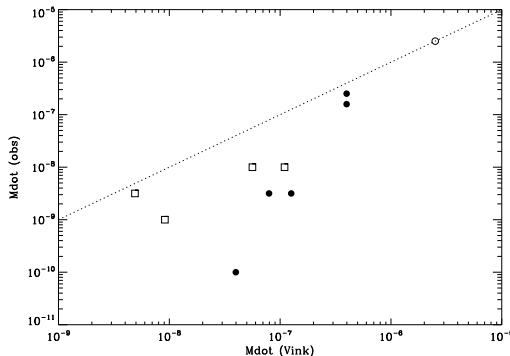


Figure 3. Comparison of observed and theoretical mass-loss rates for O-type dwarfs (filled circles) and giants (open circles) in the SMC cluster NGC346, from Bouret et al (2003). The open squares are the upper-limits derived by Martins et al (2004) for dwarfs in SMC-N81. The dotted line represents a one-to-one correspondence between observation and theory, note how the dwarfs appear to have mass-loss rates which are one to two orders of magnitude lower than the theoretical predictions of Vink et al (2001).

the most important mass-loss diagnostic, is almost a pure photospheric profile and contains essentially no information on the mass-loss rate. The UV P-Cygni profiles are also very weak, and as demonstrated by the Martins et al work, often only upper limits on the mass-loss rate are obtained. Clearly a more sensitive mass-loss diagnostic is required, one possibility being the use of the $\text{Br}\alpha$ line.

3. O7 giants and supergiants

As pointed out by Walborn et al (2000), AzV 83 is one of only two normal O7 stars in the SMC (both are of O7Iaf+ spectral type), the other being the well known star AzV 232 = Sk 80 (which is associated with NGC346). However while their optical and visual spectra are virtually identical AzV 83 is 0.9 mag fainter in M_v . In fact, as already alluded to above, the magnitude of AzV 83 lies in the range normally occupied by O7 giants. Indeed Walborn et al pointed out that it occupied an almost identical position in the HR diagram to the OC7.5 III giant AzV 69 and speculated that the latter was slow rotator while AzV 83 was initially a fast rotator on the main sequence which has evolved to higher luminosities and now coincides with the position of the more massive giant AzV 69. Support for this scenario is provided by the OC classification of AzV 69 which might indicate that its carbon abundance is primeval while that of AzV 83 is enhanced. Walborn et al discussed the additional comparison of AzV 69 with the normal O7 III giant AzV 95 which provide a striking contrast of N/C line strengths and infer that nitrogen is enhanced in AzV 95 relative to AzV 69, again supporting the scenario in which the latter is unaffected by rotation.

These qualitative comparisons between AzV 69 and AzV 83 were investigated in detail by Hillier et al (2003) who used CMFGEN to analyse their UV and optical spectra. They found that both stars have similar values of effective temperatures (approximately 32 000 K), $v \sin i$, luminosity, and mass-loss rate

Table 1. Comparison of properties of AzV 69 and AzV 83 from Hillier et al (2003) and Walborn et al (2000). Note the different clumping factors (f), spectroscopic masses and surface nitrogen abundances.

Star	Sp. type	V mag.	$v \sin i$ km/s	$\log g$	Mass (M_{\odot})	\dot{M} (M_{\odot}/yr)	f	[N/N $_{\odot}$]
AzV 69	OC7.5 III((f))	13.35	70	3.50	40	9.2×10^{-7}	1.0	0.02
AzV 83	O7 Ia f+	13.58	80	3.25	22	7.3×10^{-7}	0.1	1.8

although the UV spectrum of AzV 83 was best reproduced assuming a clumping factor of $f = 0.1$ compared to 1.0 for AzV 69. However it was also found that AzV 83 relative to AzV 69 has a lower surface gravity and consequently a lower spectroscopic mass, while the former has a surface nitrogen abundance of approximately twice solar compared with a near normal SMC nitrogen abundance for the latter. This lends strong credence to the idea expressed above that AzV 83 was initially a fast rotator but has undergone rotationally enhanced mass-loss and mixing resulting in a lower current mass and higher surface nitrogen abundance than AzV 69. Moreover, AzV 69 must have a low rotational velocity (not just $v \sin i$) since it has evolved away from the zero-age main sequence (ZAMS) but has pristine surface composition for the SMC.

4. Wind terminal velocities

Radiation driven wind theory predicts rather simple dependence of the ratio of wind terminal velocity to escape velocity such that $v_{\infty}/v_{esc} \sim \hat{\alpha}/1 - \hat{\alpha}$ where $\hat{\alpha}$ is the effective value of the force multiplier parameter α defined by Puls et al (2000). Puls et al show that the value of $\hat{\alpha}$ is rather insensitive to metallicity, at least in the range 0.1 to 3.0 times solar. Hence one expects that to first order the wind terminal velocities in the SMC should be rather similar to those of galactic stars. This is somewhat at odds with the oft-stated comment that wind terminal velocities in the SMC are lower than those in the Galaxy. Evans et al (2004a) have carefully investigated this issue using a well controlled sample of stars in the SMC which have saturated P-Cygni UV line profiles and well determined escape velocities. They find (Fig.4) that there is no significant difference between SMC and Galactic samples but it should be noted that the requirement for stars to have saturated UV resonance lines implies that the sample consists of supergiants or giants, but not dwarfs (due to the weaker winds in the SMC). Nevertheless, this result is consistent with the predictions of Puls et al and lends support to the assumption that wind terminal velocities supergiants in Local Group galaxies are similar to those of galactic stars (Urbaneja et al 2003).

We now turn to the effective temperature dependence of terminal velocities. Lamers et al (1995) and Kudritzki & Puls (2000) have shown that the ratio v_{∞}/v_{esc} depends on effective temperature and argue that a step function, with break at early B-type stars, is a good approximation to the observed trend. This step has been interpreted as a manifestation of the bistability effect in

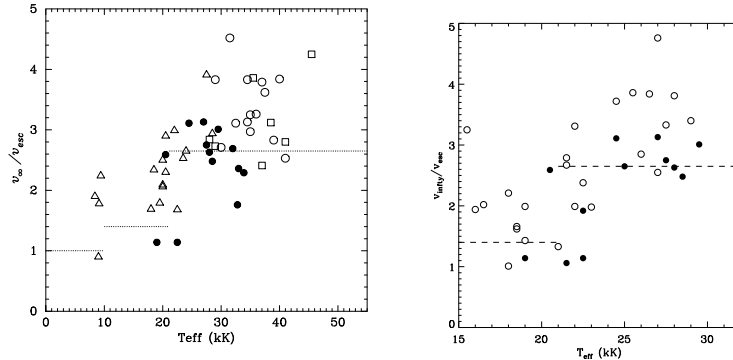


Figure 4. The left-hand panel illustrates the results of Evans et al (2004a) comparing the ratio v_{∞}/v_{esc} for OB stars in the SMC (filled circles) with Galactic results (open circles). The right-hand panel is from Crowther et al (2005) and shows improved Galactic results in the vicinity of the bistability jump at 21 000 K. In both panels the horizontal lines represent the scalings of Kudritzki & Puls (2000). These figures show the large scatter in Galactic values due to uncertain distances, similar values for SMC and Galactic stars, and poor agreement with the assumed scalings of Kudritzki & Puls.

LBV winds, while the calibration of Lamers et al is widely used, for example it is adopted in the theoretical estimation of mass-loss rates (Vink et al 2001) and in the formation of circumstellar neulae and, for example, their impact on GRB light curves. We can see from Fig.4 (left panel) that the latest observational data do not lend strong support to this calibration, the galactic data in particular have significant scatter due mainly to the uncertain distance to galactic OB stars. Crowther et al (2005) have looked in more detail at the B-type bistability jump at 21 000 K (Fig.4, right-hand panel) and show that for galactic B-type supergiants the trend is more gradual than step-like. Note also that these new results for Galactic supergiants are in good agreement with the SMC results of Evans et al (2004a).

5. Rotation and surface composition

The surface composition of a massive star may be modified during its evolution by mass-loss, rotationally induced mixing, mass-transfer (in binary systems) and magnetic fields. We do not consider the very important topic of massive binary evolution here, but consider only predictions of those calculations for single star evolution which include mass-loss and rotation, the most obvious spectroscopic consequence of which is an enhanced surface nitrogen abundance. Since the pristine nitrogen abundance of the SMC is $1/30^{\text{th}}$ solar evolutionary effects on the surface nitrogen abundance of massive stars are much easier to detect in the SMC than in our Galaxy or the LMC. Fig.5 represents a compilation of the surface nitrogen abundances for O and B-type stars in the SMC. This sample contains results for all the objects shown in Fig.1, (Lennon et al 2003, Bouret et al 2003, Hillier et al 2003, Trundle et al 2004, Heap et al 2005, Evans et al 2004c) with additional results from recent work on B-type supergiants in the

SMC (Trundle & Lennon 2005, Dufton et al 2005). The evolutionary tracks are from Maeder & Meynet (2001) for an initial rotational velocity of 300 km/s.

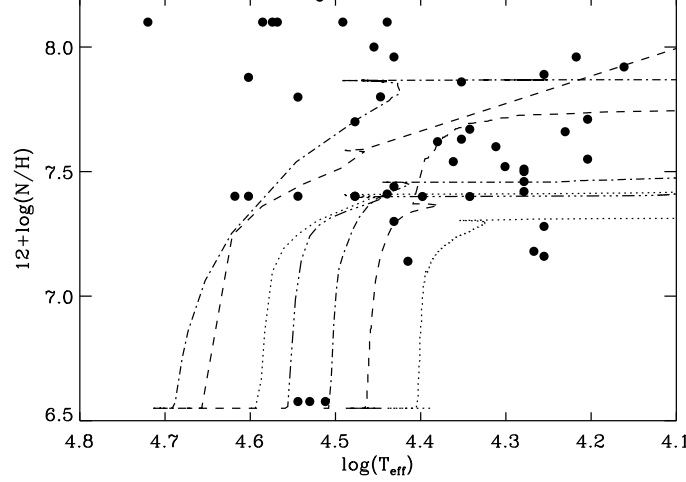


Figure 5. Surface nitrogen abundances of SMC OB stars as a function of effective temperature compared to the predictions of the Maeder & Meynet (2001) calculations for an initial rotational velocity of 300 km/s and for initial masses 60, 40, 25, 20, 15, 12 and 9 solar masses. Typical error estimates for stars with $\log(T_{eff}) < 4.5$ are ± 0.2 . The pristine SMC nitrogen abundance is taken to be 6.55 dex.

One can see that most OB stars show enrichments in nitrogen by a factor of 10 or more, comparable to that exhibited by the evolutionary tracks at the end of the main sequence. For the O9/B-type stars, those with $\log(T_{eff}) < 4.5$, this is what one might expect since these objects are all evolved stars (refer to Fig.1). For O-type stars, while it appears that the nitrogen enrichments are rather higher than one might expect from the evolutionary tracks, one must bear in mind that there are few quantitative error bars for the O-type stars (these are typically 0.2 dex for the O9/B-type objects). These abundances are typically derived from spectrum synthesis fits, clearly more quantitative estimates are desired. However there is a more serious problem concerning Fig.5 which is that the mean $v \sin i$ for the B-star and O-star samples are 65 and 67 km/s respectively, much lower than the initial rotational velocity of the models, and the terminal age main sequence rotational velocities of ~ 200 km/s. This problem has been discussed by Herrero & Lennon (2004) in the context of Galactic OB stars, and may point to a problem with the angular momentum evolution of the models. One must bear in mind however that since we cannot derive reliable metal abundances for stars with $v \sin i$ greater than ~ 120 km/s we are biased towards stars with low $v \sin i$, and hence also low v .

In an interesting investigation of two pole-on Be stars in the SMC cluster NGC330, Lennon et al (2005) showed that there is strong evidence that they are not enriched in nitrogen raising the interesting possibility that rotational mixing is not an efficient process for stars in this mass range ($\sim 10 M_{\odot}$). While one might speculate about the inhibiting influence magnetic fields in massive stars,

stellar evolution calculations are so far exploratory (Maeder & Meynet 2004) and quantitative predictions of surface abundances for such models are lacking.

Finally we note that Maeder et al (1999) raised the interesting possibility that stellar rotation depends on metallicity, based on the observed dependence of the fraction of Be stars in clusters in the Galaxy, the LMC and the SMC. This idea was strongly driven by the high fraction of Be stars found in the SMC cluster NGC330 of 40%, together with a perceived low fraction of Be stars in clusters in the solar neighbourhood. However Pigulski & Kopacki (2000) have found a similarly high number of Be stars of $36 \pm 7\%$ in the cluster NGC7419 which is 2 kpc towards the galactic centre indicating that there exists large statistical fluctuations in the Be star fraction at a given Z . Penny et al (2004) concluded that there was no dependence on Z for O-type stars in the Galaxy, LMC and SMC but their samples for the LMC and SMC consisted of only 19 and 15 stars respectively and suffer from the same bias to narrow-line stars discussed in the previous paragraph. Furthermore Keller (2004) investigate ~ 100 B-type cluster and field stars in the LMC and concluding that there is mild evidence for faster rotational velocities than their galactic counterparts. Clearly, the task of correlating abundance anomalies with rotational velocities requires the use of larger unbiased samples, such a project is discussed by Evans et al elsewhere in these proceedings.

Acknowledgments. DJL would like to thank all the participants of GO7437 and 9116 including Rolf Kudritzki, Nolan Walborn, Joachim Puls, Adi Pauldrach, Linda Smith, Sally Heap, Max Pettini, Steve Smartt, Thierry Lanz, Ivan Hubeny, Norbert Langer, Claus Leitherer, Joel Parker, Timothy Heckman. We also acknowledge support of PPARC under grant PPA/G/S/2001/00131.

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